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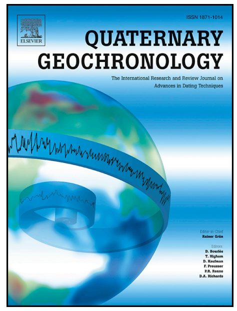

First Holocene cryptotephras in mainland Australia reported from sediments at Lake Keilambete, Victoria, Australia

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PII: S1871-1014(16)30109-1

DOI: 10.1016/j.quageo.2016.08.007

Reference: QUAGEO 787

To appear in: *Quaternary Geochronology*

Received Date: 30 November 2015

Revised Date: 4 August 2016

Accepted Date: 16 August 2016

Please cite this article as: Smith, R.E., Tyler, J.J., Reeves, J., Blockley, S., Jacobsen, G.E., First Holocene cryptotephras in mainland Australia reported from sediments at Lake Keilambete, Victoria, Australia, *Quaternary Geochronology* (2016), doi: 10.1016/j.quageo.2016.08.007.

First Holocene cryptotephras in mainland Australia reported from sediments at Lake Keilambete, Victoria, Australia

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Abstract

We report the first observations of Holocene cryptotephra deposits in lacustrine sediments from mainland Australia. All counts of cryptotephra shards are presented, but we focus on two prominent peaks of dark coloured glass shards representing distinct cryptotephras within the sediments of Lake Keilambete, Victoria, southeast Australia. These two basaltic cryptotephras, aged 4589-3826 cal BP and 7149-5897 cal BP, may have derived from eruptions of Mts Gambier or Schank, South Australia. In addition, colourless shards, most likely of silicic composition and therefore unlikely to emanate from an Australian volcano were observed, suggesting a distant volcanic source beyond Australia. The presence of both the 'local' basaltic shards and the distal silicic shards highlights the potential to identify isochronous marker horizons in southern Australian sediments, thus potentially enabling a long-term goal of establishing a novel chronostratigraphic tool based on a cryptotephra network.

Keywords

Tephra, volcano, palaeoclimate, Mount Gambier Volcanic Province, Newer Volcanic Province

1. Introduction

Tephrochronology has become one of the principal geochronological techniques in Quaternary science, and this has been extended by the use of tephra not visible to the naked eye, cryptotephras (e.g. Turney 1998; Blockley et al., 2008; Lowe, 2011). Tephra and cryptotephras are characterised by their morphology and geochemical composition, coupled with stratigraphic and chronological data to provide correlations between distal archives and, where possible, between distal and proximal units (i.e. distant from and close to volcanic sites, respectively). The co-location of tephra between geographically separate sedimentary archives provides an important chronostratigraphic marker that can be used to establish the synchronicity, or otherwise, of climate change and/or environmental response spatially (Blockley et al., 2012; Lane et al., 2013a). Tephrochronology has been applied worldwide (e.g. Lowe, 2011), but studies are limited in Australian Quaternary sediments despite its potential usefulness in reconstructing the frequency and magnitude of past volcanic events. Moreover, such studies are highly beneficial in the assessment of contemporary and future volcanic risk (Larsen, 2008) as well as reducing chronological uncertainties in sediments which are influenced by radiocarbon reservoir effects, or where variable sediment moisture content hinders optical dating (e.g. Rieser and Wust, 2010; Wilkins et al. 2012; Reeves et al., 2013).

Australia has two major volcanic regions, namely the Western Victorian Volcanic Field (Boyce et al., 2013) and the Atherton Tableland, Queensland (Griffin and McDougall, 1975; Whitehead et al., 2007; Coulter et al., 2009). Both regions had active volcanoes as recently as the Holocene and may have provided a source of tephra to suitable archives. Australia's two youngest volcanoes, Mt. Schank and Mt. Gambier, last erupted in the mid-Holocene, ~5,000 years ago (Smith and Prescott, 1987; Gouramanis et al., 2010) (Figure 1). They are located in southeast South Australia, where dominant westerly winds could have dispersed tephra across the southeast of Australia, including over the lakes of the Newer Volcanic Province (NVP), Victoria, where many of Australia's key Quaternary palaeoclimate records are found (Gouramanis et al., 2013). The prevailing global wind patterns during the Holocene additionally suggest that there is potential for remotely sourced tephra from South America, Indonesia, Papua New Guinea, and New Zealand to be deposited in Australian sediments (e.g. Coulter et al., 2009; Fletcher and Moreno, 2012). Coulter et al. (2009) made the first observation of a distally sourced cryptotephra in an Australian Quaternary sedimentary sequence - the Marine Isotope Stage 5a (75-90,000 cal BP) sediments of Lynch's Crater, Queensland. However, no further cryptotephra investigations have been reported, either from regions outside of Queensland, or for other periods of time.

Here, we investigate cryptotephra preservation within the Holocene sediments of Lake Keilambete, Victoria, which sits in the centre of the NVP and downwind of the Mount Gambier Volcanic Province.

2. Regional Setting

Lake Keilambete (38º12’27.76”S 142º52’44.94”E) lies ~30 km north of Bass Strait and ~170 km southwest of Melbourne (Figure 1), overlying Miocene limestone within the Western Victorian NVP (Ollier and Joyce, 1964; De Deckker, 1982; for full description of the NVP see Boyce, 2013). The site was chosen for its chronological control, previous Holocene palaeoclimate research and positioning relative to favourable meteorological flowpaths and mid-latitude westerly fronts (Bowler, 1981; De Deckker, 1982; Jones et al., 2001; Wilkins et al., 2012). Lake Keilambete is an isolated, steep-sided, flat-bottomed, saline (70 g/l), holomictic maar crater lake. The lake is currently ~9 m deep, with water levels predominantly driven by changes in precipitation/evaporation and a small groundwater influence (Bowler and Hamada, 1971; Jones et al., 2001; Wilkins et al., 2012). The lake catchment area is 4.2 km^2 and the lake surface area is 2.7 km^2 (Wilkins et al., 2012, 2013). Thorough age-depth analysis of the basin has recently been undertaken, indicating that the upper ~5 m of sediments from the depocentre of the lake are Holocene in age (Wilkins et al., 2012).

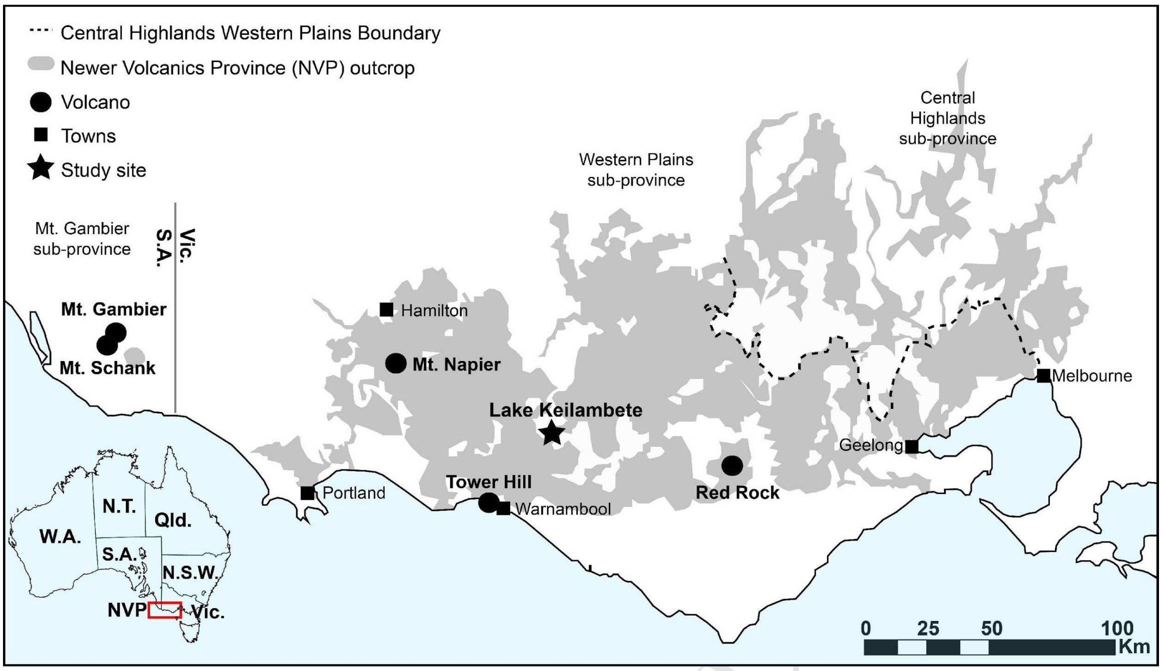

Figure 1: Western Newer Volcanics Province of southwestern Victoria (Australia inset) and southeastern South Australia, indicating location of Lake Keilambete, volcanic areas mentioned herein and nearby towns (modified after Boyce, 2013).

3. Methods

3.1 Core recovery and sub-sampling

Core LK2012 was obtained from a pontoon using an Aquatic Instruments Universal corer to capture the sediment-water interface, followed by a Geo-Corer to collect deeper sediments. Sediment cores were stored at 4ºC prior to subsampling. The water depth above the coring site was 7.8 m. A total of 5.06 m of sediment was collected, consisting of 6 cores. Sediments between 0-3.82 m (the Holocene section) were sub-sampled at 1 cm intervals for cryptotephra analysis. The sediments consisted of an upper unit of dark calcareous muds, with calcareous laminations (=*Upper Keilambete Muds* sensu Bowler, 1970; De Deckker, 1982) between 0-185 cm and fine dark grey muds with minor carbonate (=*Lower Keilambete Muds* sensu Bowler, 1970; De Deckker, 1982) between 185-362 cm. The lowermost 20 cm of sediment (362-382 cm) comprises laminated grey-green clays and are equivalent to the ‘grey clays’ identified by Wilkins et al. (2013) (Figure 2; Supplementary Information 1).

3.2 Cryptotephra-derived glass shard isolation and identification

The extraction and concentration of glass shards were undertaken in accordance with the methodology outlined in Blockley et al. (2005), adapted from Turney (1998). Sieving was undertaken using 80 µm and 15 µm nylon meshes, and density separation was achieved by flotation in sodium polytungstate (SPT; $Na_6[H_2W_{12}O_{40}]$) with densities of 2.3 and 2.5 g/cm^3 (modified from Blockley et al. 2005). We took rangefinder samples of 10 cm thickness, equivalent to 1 cm^3 sediment, at 10 cm intervals and extracted and counted glass shards. We then identified the three zones with the highest concentrations of shards and, across these three zones, sampled at 1 cm thickness, equivalent to 1 cm^3 sediment, at 1 cm intervals and extracted the shards and counted them. Due to the potential occurrence of basaltic shards, both light and heavy extractants were analysed (see Blockley et al., 2005 for details).

3.3 Sediment age model

The sediments of core LK2012 were correlated to core Keil02 of Wilkins et al. (2012) by visual comparison of distinctive marker horizons from X-ray images of Keil02 and optical and X-ray images of LK2012 obtained using an ITRAX™ core scanner at the Australian Nuclear Science and Technology Organisation (ANSTO) (Supplementary Information 2). This allowed for the published radiocarbon and optically stimulated luminescence (OSL) dates from Keil02 (Wilkins et al., 2012) to be transferred to LK2012 depths. In addition, seven bulk sediment samples from LK2012 were analysed for ^{14}C using the Centre for Accelerator Science (CAS) facility at ANSTO

(Supplementary Information 2). Bulk organics from the sediment samples were used as limited sediment sample sizes precluded the isolation of organic or carbonate macrofossils in sufficient mass. Sediment samples were pre-treated using the standard acid-base-acid (ABA) procedure. The pre-treated material was combusted to CO_2 using the sealed-tube technique and then converted to graphite using the H_2/Fe method (Hua et al., 2001). AMS ^{14}C measurements were carried out using the STAR 2MV tandem accelerator facility at ANSTO (Fink et al., 2004).

A reservoir correction of 670 ± 175 yrs (as per Wilkins et al., 2012) was applied to all radiocarbon dates used in this study (except one charcoal date from the Wilkins et al. (2012) sequence – Keil02_294-295). An age-depth relationship was then determined between the radiocarbon, OSL ages and combined stratigraphy using a *P_Sequence* deposition model in OxCal 4.2.3 (Bronk Ramsey and Lee, 2013) with the SHCal13 calibration curve (Hogg et al., 2013) and IntCal13 calibration curve (Reimer et al., 2013). The interpolation model was run, using outlier detection (Blockley et al., 2007; Bronk Ramsey, 2008, 2009), and a variable K factor. The depositional model was used to calculate model ages for each centimetre of the sequence and this was then used to infer the highest probability density range for the depths of the reported tephra (Bronk Ramsey and Lee, 2013). The *Boundary* function was used throughout as initial model runs demonstrated that there was a clear change in sedimentation rate toward the base of the sequence (Bronk Ramsey, 2008). All calibrated ages are reported to 95.4% confidence.

4.3 Glass geochemistry

Glass shards were prepared for major element analyses as outlined in Blockley et al.

(2005). Unfortunately, due to limited sediment availability, geochemical analysis was only possible for one sample, from 185-186cm, for which only one glass shard survived the sample pre-treatment. This shard was analysed in triplicate, but one analysis yielded results with poor total values. Analysis was undertaken at the Research Laboratory for Archaeology and the History of Art, University of Oxford. Major element analysis was obtained on a wavelength-dispersive JEOL 8600 electron microprobe (EPMA) equipped with four spectrometers set up with a low beam current of 6 nA, accelerating voltage of 15 kV, and take off angle of 40° with a 10 µm beam diameter. Secondary standards derived from the Max Planck Institute were used to verify the calibration (Jochum et al., 2006; Supplementary Information 3).

4. Results

4.1.Tephra identification and morphology

The lacustrine cores analysed here conform to previous sedimentological descriptions (De Deckker, 1982; Wilkins et al. 2012), with no visible tephra horizons. However, for the first time, cryptotephra deposits were identified in these Holocene lacustrine sediments (Figure 2). Though the concentration of both brown and colourless shards were variable throughout the core, colourless shards were present in smaller concentrations (Figure 3a, 3b).

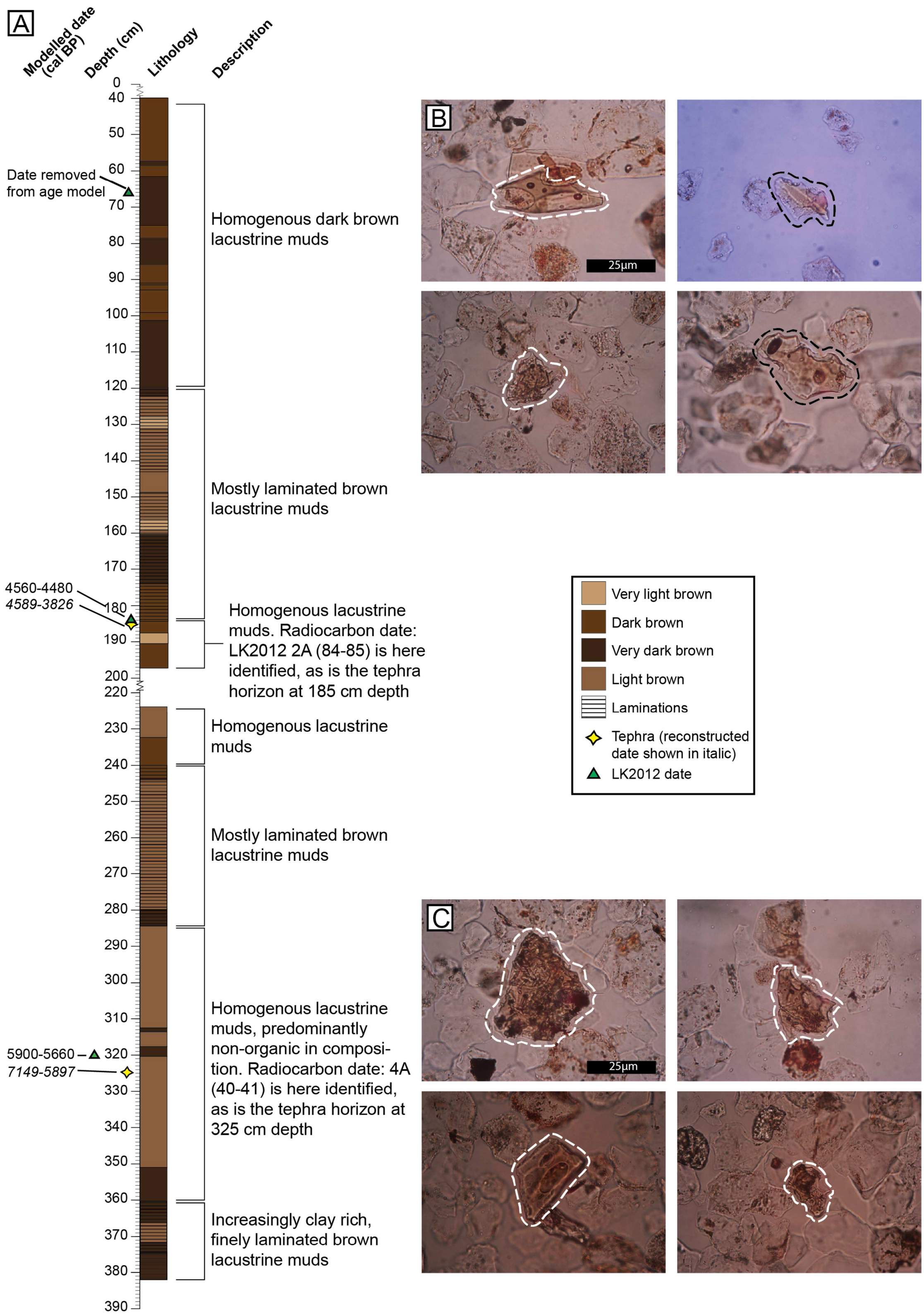

Figure 2: A) Stratigraphic column of the Holocene section of LK2012, including basic sedimentary description, identification of cryptotephras, and modelled dates (i.e. in

calibrated years BP) obtained from radiocarbon dating methods and the location of two tephra horizons; B) Representative images of glass shards isolated from between 180 and 190 cm. Scale for all shards is shown in first image; C) Representative images of glass shards isolated from between 316 and 326 cm. Scale for all shards is shown in first image.

The morphologies of coloured shards are similar throughout the entire sequence; shards are predominantly vesicular, cuspate and 20-50 μm in size (Figure 2; Table 1). Shards found in sample 316-326 cm have an increased abundance of mineral inclusions (Figure 2c). Although silicic glass is rare, those that have been identified in LK2012 sediments are fluted, pristine and close to the refractive index, making them exceptionally difficult to identify and photograph.

Table 1: Summary description of glass-shard morphology for range-finders

Depth (cm)	**Summary description of glass-shard morphology**
70-80	Cuspate and vesicular
120-130	Colourless, cuspate
160-170	Vesicular
170-180	Brown in colour. Cuspate and vesicular
180-190	Cuspate and vesicular, some with mineral inclusions. Colourless shards are present. Alteration features present in some shards
224-234	Cuspate. Shards appear weathered with hydrated silica gel layers
234-244	Green in colour. Cuspate, with hydration rims. Colourless shards have no vesicles
244-254	Brown and vesicular
254-264	Green/brown shards with vesicles and mineral inclusions
264-274	Yellow-green in colour. Cuspate and vesicular with mineral inclusions present. Colourless shards are fluted
274-284	Colourless/pink, fluted; brown, blocky shards with vesicles appearing weathered with pitting corrosion and hydrated silica gel layers
284-296	Brown shards, cuspate, vesicular and mineral inclusions present
296-306	Cuspate with mineral inclusions. Some colour leaching and pitting corrosion evident in some shards
306-316	Yellow-green in colour. Cuspate and vesicular with mineral inclusions present
316-326	Dark brown, vesicular with mineral inclusions. Some shards are very cuspate
326-336	Colourless shards are vesicular. Brown-yellow shards appear weathered with mineral inclusions, pitting corrosion and cuspate edges

336-346	Grey shards with cuspate edged and mineral inclusions
346-356	Brown shards that are cuspate and vesicular
356-366	Colourless, fluted
366-376	Green shards with vesicles, cuspate morphology and mineral inclusions. Fluted colourless shard
376-382	Grey-brown shards with cuspate edges and vesicles

4.2 Glass-shard counts

Shard concentration was greatest within the deeper sediments analysed, with three large peaks in brown shards (likely to be of non-rhyolitic chemistry) present at 316-326 cm, 306-316 cm and 180-190 cm (84, 58 and 39 shards/g respectively; Figure 3a). Consequently, these three depths were chosen for point count analysis. Upcore from the peak at 316-326 cm, glass shard concentration gradually declines – a pattern typical of prolonged transport and/or re-deposition of glass shards after an initial volcanic event (Davies et al., 2005). Sample 306-316 cm has therefore not been investigated further here. We define two further cryptotephra horizons on the basis of peak glass-shard concentrations at 185-186 cm and 325-326 cm, referred to as 185 and 325, respectively, and these will be the focus of our investigation.

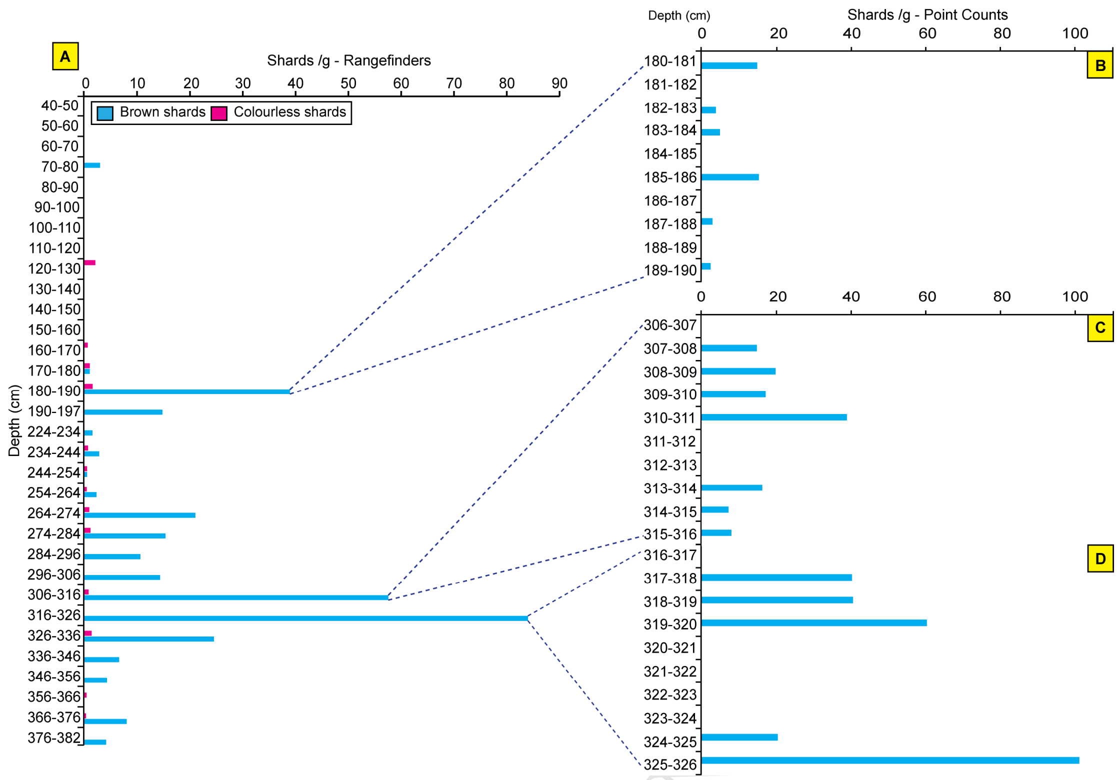

Figure 3a: Concentration of brown and colourless glass shards as presented in: A) 10 cm rangefinder samples throughout the Holocene section of LK2012; B) counts of samples between 180-190 cm; C) counts of samples between 306-316 cm; D) counts of samples between 316-326 cm.

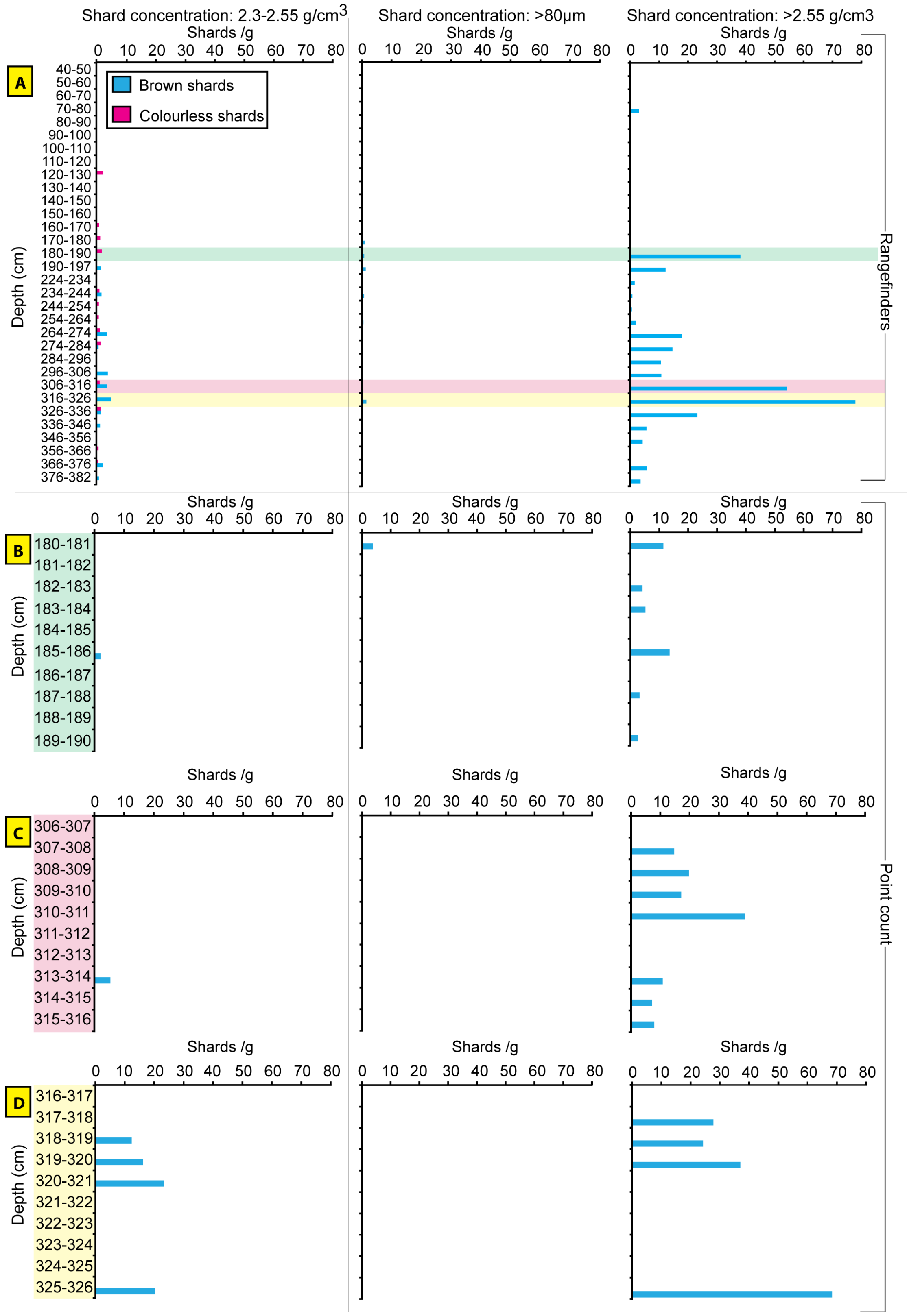

Figure 3b: Glass shard concentrations subset according to size and density properties as identified in A) rangefinder samples. Green, red and yellow colours are used across all three size/density properties to identify the locations of the high shard

concentrations within the core; B) counts of samples between 180-190 cm; C) counts of samples between 306-316 cm; D) counts of samples between 316-326 cm.

Figures 3a and 3b illustrate the glass shard concentrations at 1 cm intervals within the two aforementioned peaks to be discussed further. The counts across 180-190 cm indicate a bimodal distribution with two larger peaks across the 10 cm interval. While neither of these are as large as the peak of the initial rangefinder count, their sum almost matches the initial rangefinder counts. The peak glass concentration at 185 cm is not bracketed by high concentrations immediately above or below, and the morphology of the glass shards at 185 cm is different from that of other glass-shard deposits observed. This suggests that the glass shards at 185 cm depth represents a mid-Holocene volcanic event unrelated to the glass shards at 325 cm depth.

Low concentrations of colourless glass shards are present at various points throughout the sequence, with a maximum of 2.07 shards/g at 120-130 cm (Figure 3a). The low concentrations of these colorless glass shards in combination with limited sediment precludes further analysis at this time.

4.2 Age modelling

The age-depth model (Figure 4) demonstrates well-constrained dates through the Holocene and provides two reconstructed dates for the deposition of glass shards at 185 cm and 325 cm depth; these are 4589-3826 cal BP and 7149-5897 cal BP respectively, when run on a 1cm interpolation model. One date, KMB1D/466-467, was reported as an outlier and has been down-weighted in its contribution to the age model. KMB1D/20-21 was reported as an outlier and has been removed from the age model (Bronk Ramsey, 2009; Supplementary Information 2).

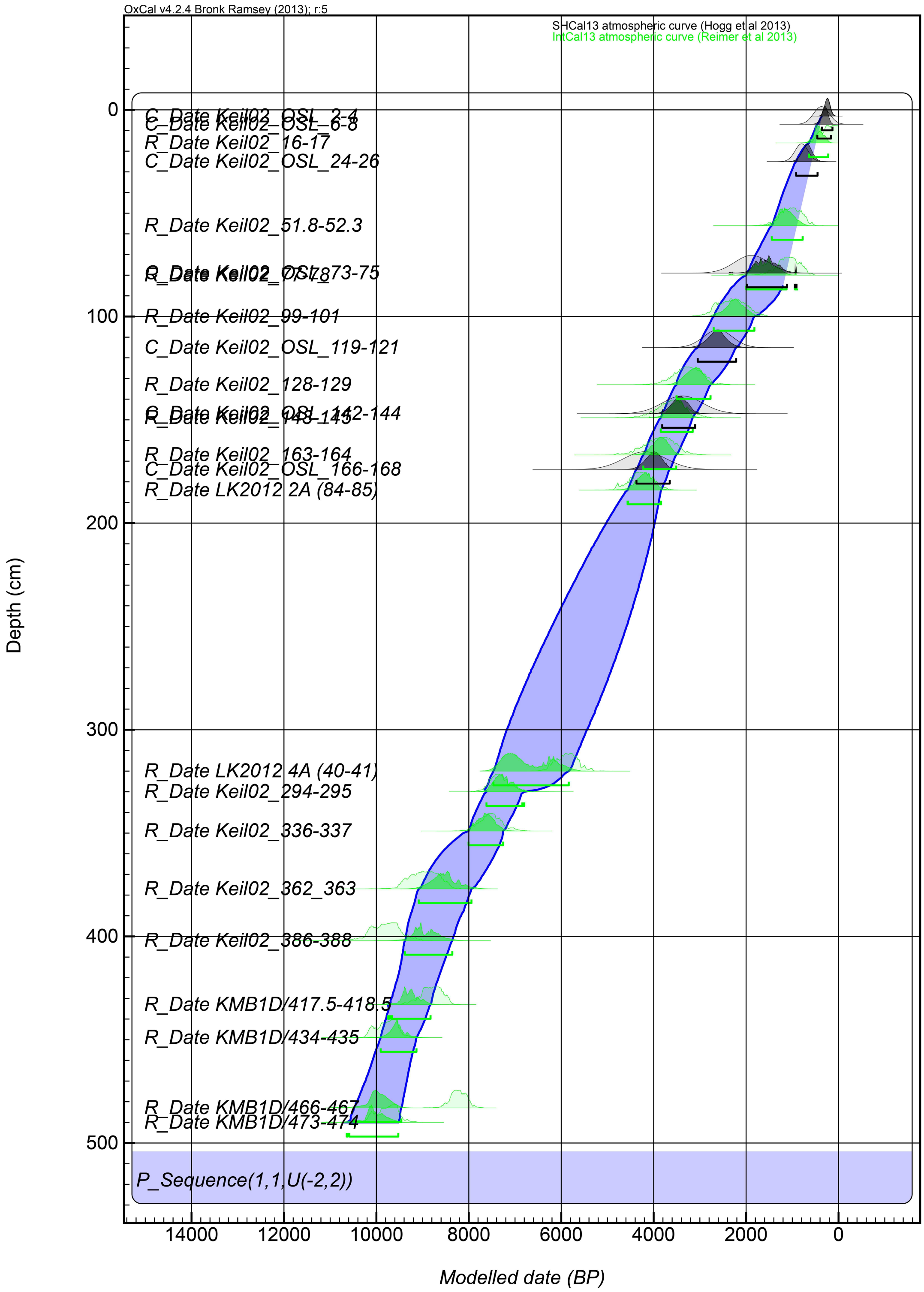

Figure 4: Age-depth model based upon visual stratigraphic alignment with core Keil02 (Wilkins et al. 2012), with the addition of radiocarbon dates obtained from core LK2012 and radiocarbon and OSL dates from core Keil02 (Wilkins et al. 2012). Uncalibrated radiocarbon dates on bulk organics in sediments obtained from ANSTO for Lake Keilambete are referred to as R_date_KMB1D or R_date_LK2012; radiocarbon dates obtained from Wilkins et al (2012) are referred to as R_date_Keil02. Radiocarbon dates have been used to model calibrated ages of OSL dates obtained from Wilkins et al. (2012) and are referred to as C_date_Keil02_OSL. See Supplementary Information 2 for further information.

4.3 Glass shard analysis

The geochemical composition of glass shards identified at 185 cm depth is consistent with glass of basaltic affinity based on the SiO_2, MgO and CaO content (Table 2). The replicated analyses yielded one poor total (81.53 wt%) likely due to the small size of the shard analysed, but the elemental ratios are broadly consistent with the two analyses presented in Table 2 (Supplementary Information 3).

Table 2: Normalised geochemical analysis of glass shards from the sample at 185 cm depth presented as wt%. Total value represents non-normalised total values. RH0601_5_1 and RH0601_5_2 analyses are both obtained from one glass shard.

Label	**SiO_2**	**TiO_2**	**Al_2O_3**	**FeOt**	**MnO**	**MgO**	**CaO**	**Na_2O**	**K_2O**	**P_2O_5**	**Cl**	**Tot**
RH0601_5_1	48.18	2.87	16.17	10.59	0.23	4.17	8.88	4.45	3.35	0.99	0.12	96.50
RH0601_5_2	48.41	2.89	16.50	10.34	0.15	4.00	9.39	4.29	2.91	1.00	0.12	97.24

5. Discussion

5.1 Basaltic cryptotephras in the Holocene sediments of Lake Keilambete

Marked hydroclimatic shifts are well known for southern Australia (Wilkins et al., 2013; Gouramanis et al., 2013; Barr et al., 2014), including for Lake Keilambete, which underwent episodic lake shallowing through the Holocene (Wilkins et al., 2013). However, temperature changes during the Holocene were insufficient to produce landscape instability, and vegetation changes in the region are thought to have been negligible until the arrival of Europeans in the 1840s (Bowler and Hamada, 1971; Mooney and Dodson, 2001; Mills et al., 2013). Therefore, it is highly unlikely that post-depositional changes have influenced the LK2012 tephrostratigraphy. Based on this palaeoclimatic interpretation, along with sedimentological characteristics and shard morphology, we interpret both Holocene tephra peaks at 325 and 185 cm depth to be the result of a primary ash-fall.

Some glass shards identified at 185 cm depth exhibit possible alteration features, such as hydration rims and smoothed cuspate edges which may be indicative of subaerial exposure (Figure 2B). Alternatively, lake level controlled changes in the pH of lake water and sediment may have influenced the chemical weathering of shards and produced the features seen (Pollard et al., 2003). Age-modelling places this cryptotephra deposit at 4589-3826 cal BP. This time period coincides with increased evaporation at Lake Keilambete and reconstructions in lake-level indicate several minima at ~2.3, 2.8, 3.5 and 3.9 cal kyr BP (Wilkins et al., 2013).

5.2 Silicic cryptotephra

It is increasingly being found that tephra deposits may be distributed across larger distances than previously documented (Davies et al., 2005, 2012) and cryptotephras are now commonly identified many hundreds to thousands of kilometres from the source region (Shane, 2000; Wastegåard et al., 2000; Pearce et al., 2004; Lane et al., 2011; 2013b; Pyne-O'Donnell et al., 2012; Jensen et al., 2014; Lowe, 2014). Within LK2012, there are sporadically distributed, colourless shards which are fluted and present at low concentrations throughout. Local volcanic sources from southern Australia are entirely of basaltic affinity, with no major magma evolution reported, and hence would not have produced colourless, silicic shards during the Holocene (Lesti et al., 2008; Boyce, 2013). Consequently, we suggest that the colourless cryptotephras found in the Holocene sediments of Lake Keilambete must have been sourced from distal volcanic regions such as New Zealand, Papua New Guinea, Indonesia or South America. Their shard morphology suggest that they are primary tephra-fall deposits. Geochemical characterisation is needed to source eruptions for them. However, very low concentrations found in LK2012 currently preclude such analyses. Further investigation using larger sediment samples - e.g. through collection of multiple or wide-diameter cores - is therefore required to isolate the colourless glass shards in higher concentrations.

5.3 The ages of the cryptotephras and regional comparison

Attempting to correlate potential and known eruptions is difficult as volcanoes in the area are not presently constrained by robust chronologies and the complexity of volcanism in the NVP is underestimated (Blaikie et al., 2014). On the basis of the Wilkins et al. (2012) age model, transferred to core LK2012 via visible stratigraphic matching, the age of the glass shards identified at 325 cm depth is estimated to be 7149-5897 cal yr BP (Figure 4). Tower Hill and Mt. Napier were two potential correlatives, but the dates established for these eruptions are highly uncertain and may be much older than the cryptotephra occurrences in Lake Keilambete. For example, the eruption of the Tower Hill volcano, Victoria, was dated to between 8700 and 6500 yr BP by Gill (1978) using mammillary calcite. However, D'Costa et al. (1989) has since placed the age of the most recent ash layer at >20 kyr BP by radiocarbon dating organic remains. Most recently, Sherwood et al. (2004) suggest that the eruption occurred earlier, at 35 ± 3 ka, based on average values from radiocarbon and thermoluminescence dating of bulk and sand sediments as well as plant macrofossils. Similarly, it was believed that the Mt. Napier volcano erupted at 7240 ± 140 yr BP based on a minimum radiocarbon age derived from Buckley Swamp (Gill and Elmore, 1973) but samples have been re-dated using cosmogenic dating to produce an age of 31.9 ± 2.4 kyr BP (Stone et al., 1997). We therefore conclude that there is no decisive contemporary basaltic eruptive that matches to glass shards identified at 325 cm depth at this time.

Using the chronology developed in this study, the glass shards identified at 185 cm depth was deposited between 4589-3826 cal yr BP. Around this time period, the only volcanoes within the NVP likely to have erupted are Mt. Gambier and Mt. Schank, South Australia (Figure 1). Although some research has led to estimates of a Mt. Gambier eruption at 1410 ± 90 yr BP (Kigoshi and Kobayashi, 1966, in Blackburn et al. 1982), a growing consensus places this eruption between 5.5 cal kyr BP on the basis of radiocarbon dating of basal lake sediments (Gouramanis et al., 2010) to 4.3 cal kyr BP on the basis of thermoluminescence dating (Blackburn et al., 1982) (see Murray-Wallace, 2011 for an overview). Mt. Schank is estimated, from thermoluminescence dating, to have erupted at 4.9 ± 0.54 kyr BP (Smith and Prescott, 1987). Therefore, either volcano is currently a possible candidate for the origin of the glass shards identified at 185 cm depth.

While NVP eruptions are not dominated by explosive ejecta (Nicholls and Joyce, 1989), van Otterloo and Cas (2013) argued that the Mt. Gambier eruption is likely to have reached 4 on the Volcanic Exclusivity Index (VEI) (VEI: Newhall and Self, 1982), and it is therefore possible that glass shards from Mt. Gambier were dispersed farther than the ~10-20 km currently documented (Lowe and Palmer, 2005). At the time of the Mt. Gambier eruption, the wind direction is also expected to have carried plumes to the east, towards Lake Keilambete (van Otterloo and Cas, 2013). The shard morphology of the glass identified at 185 cm depth shows similar characteristics to glass in proximal Mt. Gambier volcanic ash deposits, including cuspate edges and vesicles, but there are fewer microlite inclusions in the glass identified at 185 cm depth than in Mt. Gambier glass (Sheard et al., 1993; Lowe and Palmer, 2005; Lowe, 2011). Our geochemical analysis of a single glass shard from the tephra at 185 cm depth is consistent with a Mt. Gambier or Mt. Schank origin (the two appear geochemically indistinct) (Lowe, 2011; D. J. Lowe, pers. comms.) but due to sample size, our data are insufficient to confirm this possible origin. Consequentially, we speculate that the glass identified at 185 cm depth is correlative to either Mt. Gambier or Mt. Schank eruptives, with significant potential for further discovery of this tephra within other mid-Holocene sediments across southern Australia.

6. Conclusions

The first descriptions of Holocene cryptotephras within Australian lake sediments are made from Lake Keilambete, Victoria. Both colourless and brown shards were observed, the latter with a likely local, basaltic origin. Two relatively high concentrations of brown glass occur at 185 cm depth (aged 4589-3826 cal yr BP) and at 325 cm depth (aged 7149-5897), which we deem to represent two distinct cryptotephra deposits. The older of the two at 325 cm depth currently has no known correlative within the published literature. However, the younger tephra at 185 cm depth may have derived from Mt. Gambier or Mt. Schank, South Australia, which likely erupted in the mid-Holocene. Further research is therefore required to both re-evaluate the proximal evidence for late Quaternary volcanic eruption dates in southeastern Australia and to geochemically characterise both distal and proximal tephras for the purpose of glass shard provenancing. Nevertheless, our results highlight considerable potential for the future application of tephrostratigraphy to constrain both volcanic histories and sediment accumulation dates across southern Australia. Of particular note are the colourless glass shards present in low concentrations within the sediments of Lake Keilambete. These shards, likely to be silicic, must have originated from volcanoes beyond Australia, and thus represent deposits from long distance transport. The concentration of colourless shards at Lake Keilambete precluded geochemical analysis, but future analyses of larger amounts of sediment from different sedimentary archives may enable them to be characterised and potentially correlated. In doing so, they will provide a means of continental scale chronostratigraphic correlation, of significant value to a range of palaeoclimate, palaeoecological and palaeoanthropological research.

Acknowledgements

The Adelaide University Environment Institute is thanked for financial support of travel and analytical costs associated with this project. Funding was also provided to

Jessica Reeves by the Australian Institute of Nuclear Science and Engineering (AINSE) grants ALNGRA12026 & 13008 and the Collaborative Research Network. Naomi Keller, Matiu Prebble, Katy Flowers, Patricia Gadd, Megan Williams and Haimish Prodan are thanked for their laboratory, field support and/or assistance. David Lowe is thanked for his discussions regarding unpublished cryptotephra from Mt. Gambier, Mt. Schank and general volcanology in the NVP. Erin Matchan and David Phillips are thanked for discussions concerning unpublished Ar/Ar dates on NVP basalts. Chris Gouramanis is thanked for discussions regarding the history of Lake Keilambete. Daniel Quinn is thanked for his illustrative support in Figure 2. Editorial handling by Thomas Higham and Christine Lane, and reviews by David Lowe, have greatly improved this manuscript.

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